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Effects of Incorporating Recycled Brick and Stone Aggregate as Replacement of Natural Stone Aggregate in Concrete

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Abstract

This paper presents an experimental research on the mechanical properties of concrete made from recycled and virgin coarse aggregates. Two types of recycled coarse aggregate (RCA) i.e. recycled brick aggregate (RBA) and recycled stone aggregate (RSA) were used in combination with natural stone aggregate (NSA). This study aims to investigate the feasibility of using recycled materials in concrete by focusing on the fracture mechanism of the specimens. For this purpose, sixty-six cylindrical specimens and thirty-three prismatic specimens were cast using 0, 10, 20, 30, 40 and 100% RBA and RSA as a replacement of NSA with different absolute water/cement (w/c) ratio. The test results show that the compressive, flexural and splitting strengths of concrete made from RSA were greater than those of RBA. Besides, concrete contains RSA has the lower strengths fall than that of concrete contains RBA in each percentage of recycled aggregate. The RSA concrete showed combined failure of concrete; on the contrary, aggregate failure which is not acceptable for good quality concrete has been observed in RBA concrete. Therefore, the use of RBA with NSA is not appropriate to produce good quality concrete, but replacing NSA with up to 30% of RSA can be effectively used.

Keywords: recycled brick aggregate, recycled stone aggregate, fracture mechanism, absolute w/c ratio

1. Introduction

The construction industries play a paramount role in consuming a huge amount of natural resources for construction purposes and generating construction waste from demolition works. The construction waste is non-biodegradable and at the same time its dumping is costly, therefore they are considered as the greatest difficulties and worries of the construction industries. As a small country like Bangladesh, there are scarcity disposal site, so attention has been placed on the protection of the environment and the natural resources, also the recycle of the wastes materials. The structural concrete with RCA produced from the demolition waste has great potential to optimize the impact on the environment effectively. In recent years, certain countries have considered the re-utilization of construction and demolition waste as a new construction material and as one of the main objectives with respect to sustainable construction activities. Many researchers studied the mechanical behavior of recycled concrete coarse aggregates and pointed out the possibility of using recycled aggregates (RA) to produce structural concrete [1-5]. Although it is commonly believed that RCA has high porosity, low apparent density, and high water absorption, compared to the concrete made with virgin aggregate, it can be used to produce high strength (50 MPa) structural concrete with durability properties [6].

To investigate the failure mechanism in tension and in compression of RCA concrete, Casuccio et al. [7] considered three series of concretes with different compressive strength levels. In each series, concrete specimens were prepared with

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natural crushed stone and two different RCAs. Those different RCAs were obtained by crushing both normal strength and high strength concretes. Due to the concrete made with RCA presented lightly lower strengths (1-15%), lower modulus of elasticity (13-18%) and significant reductions in the energy of fracture (27-45%); it has been compared with a concrete prepared with natural coarse aggregates on the fracture zone size. In addition, the results indicated the increase in bond strength and the reduction in stiffness, raised the elastic compatibility between concrete phases (mortar and coarse aggregates), and modified the fracture process. Corinaldesi [8] investigated the mechanical behavior and elastic properties of RA concrete. By alternatively using two different RA fractions, such as coarse and finer coarse rubble made of recycled concrete coming from a recycling plant, the concrete specimens were produced. In this study, 30% finer RCA was replaced by fine gravel and 30% coarser RCA was replaced by gravel to prepare the test specimens, and only the virgin aggregates was considered as a reference. The results of compression tests showed that structural concrete up to 32 MPa (from cylinder test) and 40 MPa (from cube test) can be manufactured by replacing 30% virgin aggregate by coarse RA.

Safiuddin et al. [9] used RCA to produce high-workability concrete substituted 0, 30, 50, 70 and 100% natural coarse aggregate by weight. The test results revealed that RCA significantly decreased the workability of concrete and also affected the compressive strength, modulus of elasticity, and permeable voids of concrete. At the age of 28 days, concrete made with 100% RCA provided 12.2% lower compressive strength and 17.7% lesser modulus of elasticity than the control concrete. Another experimental research was carried out by Peng et al. [10] on the mechanical properties of RCA concrete obtained from demolished concrete structures. Thermal treatment was applied to remove attached mortar from RCA and the concrete samples were prepared with low and high water/binder ratios of 0.255 and 0.586. The results showed that the compressive strength of RCA concrete was lower than that of control concrete at an identical water/binder ratio. The decrease of strength confirmed that the process of heating and removal of attached mortar induces micro-cracks in gravel.

However, many researchers conducted experiments on RBA to produce structural concrete and to know the mechanical properties of concrete made with RBA. Cachim [11] evaluated the properties of concrete made with two types of crushed bricks replacing natural aggregates considering w/c ratios of 0.45 and 0.5. The tested results indicate that the type and manufacturing process of bricks seem to influence the properties of the resulting concrete. Also, the properties of concrete with bricks indicate the possibility of using this type of concrete in precast applications. Aliabdo et al. [12] conducted a comprehensive experimental program using RCA obtained from the demolition of brick buildings. The test results of concrete specimens confirm that the increase in the crushed clay brick aggregates decreases concrete compressive strength, modulus of elasticity, concrete splitting-tensile strength, and increases concrete porosity. To avoid strength reduction, they strongly recommended that the percentage of coarse aggregate replacement by RCA should be limited to 25% and 50% for concrete containing cement content of 350 and 250 kg/m^3 respectively.

Mohammed et al. [13] found that there is no noticeable difference in failure patterns and flexural behavior among reinforced recycled brick concrete beams and virgin picket brick, and first-class brick concrete beams. In all of the beams, the longitudinal tension steel yielded first, followed by crushing of concrete, which is a ductile mode of failure, normally called tension failure. Whereas, in beams with higher reinforcement ratio, concrete reached its maximum capacity first, and the mode of failure was relatively brittle in nature and is usually termed as compression failure. However, in some cases, the number of cracks observed in case of recycled brick concrete beams was lower than the number of cracks in picket and first-class brick concrete beams at failure. Šipoš et al. [14] prepared mix design of brick aggregate concrete based on neural network modeling. They stated that cement content must be increased up to 20% and the w/c ratio must be decreased to achieve the same compressive strength of RBA concrete as concrete with natural aggregates. Consequently, an increase in cement amount is directly related to the replacement ratio of RBA.

Based on the literature mentioned above, it is understood that good quality concrete and high strength concrete can be produced by using the partial amount of RCA, by maintaining some specifications during the production of RCA and also in concrete mixes. However, most of the researches were carried out by the combination of the virgin or natural stone aggregate with RSA and natural brick aggregate with RBA; however, the investigation on NSA with RBA is found limited. In this experiment, these two different types of aggregates, in this experiment, were considered to be the conception of some construction industries in our country that the properties of RBA concrete can be improved, if it is used with NSA in the concrete mixes. Therefore, this study aims to investigate and compare the mechanical properties of RBA and RSA concrete in combination with NSA and to know what happens if RBA is used with NSA to produce structural concretes.

2. Recycling Process

Both types of recycled aggregates, i.e., RBA and RSA used in this study were collected from demolished reinforced concrete buildings. The concrete debris was broken down in size of 75 mm by primary jaw crusher and then taken to secondary cone crushers to break into the size ranged between 4.75 mm and 37.5 mm. RCA consists of natural coarse aggregate coated with cement paste residue, pieces of natural aggregate, or cement paste and some impurities. Consequently, two interfacial transition zones are present in concrete made with RAs; the existing interface between the original aggregate and the adhered mortar, also the new interface between the old and new mortar. The existing interface cannot be improved, and it plays an important role to achieve an effective new interface. There is a general consensus that the amount of cement paste has a significant influence on the quality, physical, mechanical and chemical properties of aggregates, and also a potential influence on the properties of recycled concrete. Existing loose cement-sand mortars with the surface of RA increase water absorption capacity and consequently decrease the strength of the produced concrete. Therefore, crashed RA was kept in a rotating steel drum and rotated for 15 minutes to reduce the amount of attached mortar from aggregate surface. Finally, the crashed RA was screened to separate various sizes of RA to the desired size ranged from 4.75 mm to 25 mm for this study.

3. Experimental Program

3.1. Constituent materials

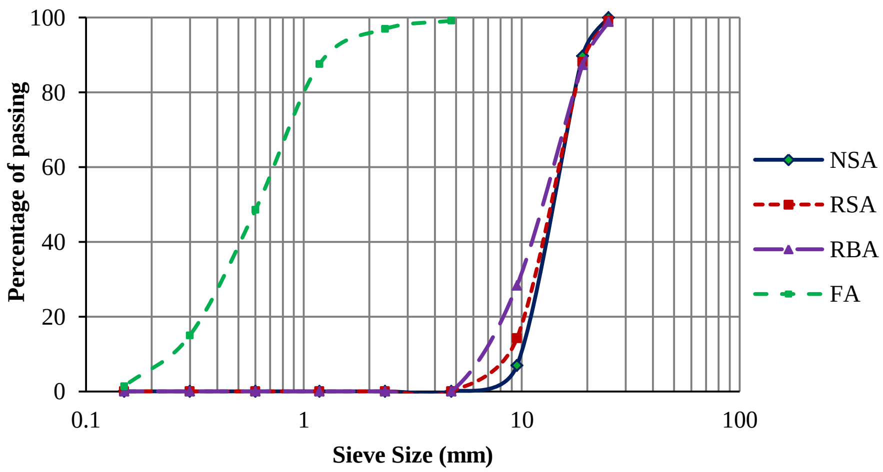


Fig. 1 Grain size distribution curve of aggregates

This study was carried out by using three types of coarse aggregates: NSA, RSA, and RBA. The NSA was in the size ranged from 4.75 mm to 19 mm whereas RSA and RBA were from 4.75 mm to 25 mm. RA contains cement mortars on its surface increase the size of the aggregates. Compared to the smaller size aggregates, the larger size aggregates give higher strength. So, sizes of the RCA were considered greater than that of natural aggregates. Grain size distribution curve of the aggregates is presented in Fig. 1. The RCA obtained from crushed field structures had more surface roughness than NSA, as noticed in Fig. 2 during visual inspection. Locally available sand having fineness modulus (FM) value of 2.51 was used as fine aggregate. Since the quality of water affects the strength of concrete, it is necessary to use pure water. So, in this study, drinking water was used to mix with the concrete, and the Ordinary Portland Cement (OPC), which specific gravity is 3.15, was used as a binder. The key physical properties of NSA, RSA, RBA, and fine aggregate (FA) are given in Table 1. The chemical compositions of the used cement provided by the manufacturer are given in Table 2.

(a) NSA (b) RSA (c) RBA

Fig. 2 Appearance of used coarse aggregates

Table 1 Basic physical properties of coarse and fine aggregates

Properties	NSA	RSA	RBA	FA
Nominal maximum size (mm)	19	25	25	2.36
Dry-rodded unit weight (kN/m^3)	16.73	14.10	12.36	14.74
Water absorption capacity (%)	0.76	3.80	5.23	2.06
Bulk specific gravity	2.65	2.31	2.03	2.62
Fineness modulus (FM)	7.03	6.98	6.84	2.51

Table 2 Chemical constituents of the used OPC (as provided by the manufacturer)

Chemical constituent	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Free lime	Insoluble residue	Loss of ignition
Percentage (%)	66.02	21.52	4.58	3.28	1.18	2.76	1.205	0.45	1.235

3.2. Concrete mixing

RSA with NSA RBA with NSA NSA

Fig. 3 Slump test of the concrete mixes

Most of the available mix design methods are based on empirical relationships, charts and graphs developed from extensive experimental investigations. Proportioning of materials is commonly done by weight proportioning method and absolute volume method. The absolute volume method involves the use of relative density values for all the ingredients to calculate absolute volume where each will occupy a unit volume of concrete. This present study has been carried out by volume proportioning method because three different types of coarse aggregates (NSA, RSA, and RBA) were used which have different characteristics and also most the construction industries in our country follow this method. The proportioning of the used ingredients was done by ACI mix design method and considered as 1:1.8:3.3 (cement: sand: coarse aggregate) by volume to make the measurement easier. The W/C ratio of 0% RCA was 0.40 since been compared to the natural aggregate, the RCA has better water absorption capacity. The extra amount of water was added into the concrete mixes by a volume of 1% of the total water for each 10% addition of both types of RCA. Water absorption capacity of RBA and RSA was measured as 1.38% and 1.17% respectively at first after 30 minutes of immersion. Then immersion for 24 hours because generally maximum 30 minutes is required for mixing and casting of concrete. Amount of extra water required for each 10% addition of RBA and RSA are 1.74 kg and 1.68 kg respectively, and 1.09% and 1.05% of water were added in 0% RCA. However, these percentages were fixed as 1% for both types of RCA due to the addition of superplasticizer to the mixes. The superplasticizer encouragingly reduces the amount of water in concrete mixes and accelerates strength development through a faster and more efficient hydration [15-17]. So, in this study, polycarboxylate superplasticizer was used to improve the workability of concrete and to maintain slump between 100 mm and 150 mm (shown in Fig. 3). The amount of superplasticizer in concrete mixes was 2% of cement with 0% RCA concrete. The amount was increased by 0.5% of the quantity of cement for each 10% increase of RA. The amount of superplasticizer and w/c ratio are tabulated in Table 3.

Table 3 Amount of super-plasticizer and w/c ratio

% of recycled aggregate	Cement kg/m^3	Water kg/m^3	Added Water kg/m^3	Total Water kg/m^3	Absolute W/C	Super-plasticizer kg/m^3	Slump mm
0%	400	160	0	160	0.40	8	137
10%	400	160	1.60	161.60	0.404	8.2	132
20%	400	160	3.20	163.20	0.408	8.4	121
30%	400	160	4.80	164.80	0.412	8.6	117
40%	400	160	6.40	166.40	0.416	8.8	116
100%	400	160	16.00	176.00	0.440	10	98

3.3. *Preparation of specimens and test procedure*

Testing of harden concrete plays an important role in controlling and confirming the quality of cement concrete work. To perform this study, sixty-six standard cylindrical specimens of Ø 100 mm x 200 mm in size were prepared and tested, among these, half of them were utilized for determining the compressive strength and remaining half were used for splitting strength test of concrete. In addition, thirty-three prismatic specimens (150 mm x 150 mm x 450 mm) were cast to compare with the flexural strengths of RA concrete and the reference concrete made normal aggregates. All test specimens were cast in two phases. In the first phase, NSA was replaced by RBA, and in the second phase, NSA was replaced by RSA. In both phases, the percentages of replacement were 0, 10, 20, 30, 40 and 100%. All specimens were tested in the laboratory after 28 days of immersion curing with normal drinking water. Three specimens were tested for each percentage of RA and the average strength of these three specimens were taken into account to compare the mechanical properties of prepared concretes. The compressive strength, splitting strength and flexural strength tests have been carried out by Universal Testing Machine (UTM), shown in Fig. 4 and 5. The load increasing rate was 2.5 kN/s for compressive strength test and 0.5 kN/s for splitting and flexural strength test as per standard specifications of ASTM C39, C496, and C293 respectively.

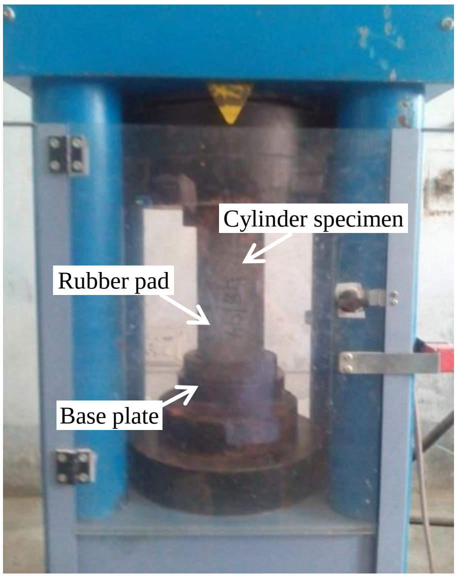


Fig. 4 Compressive strength test setup

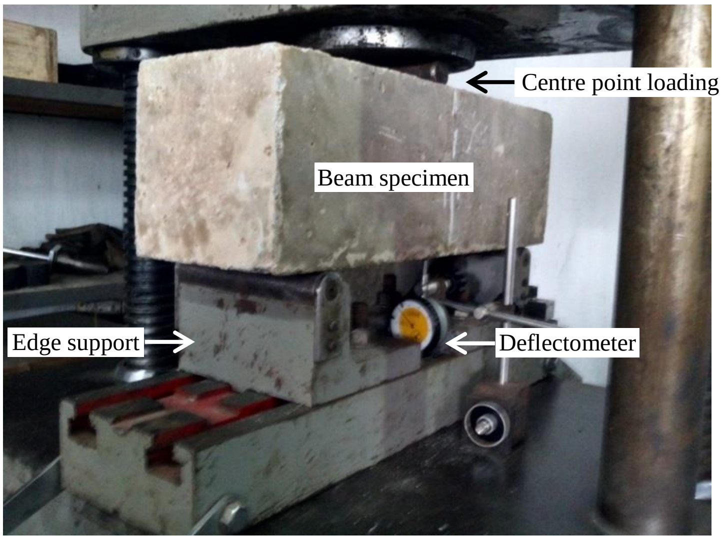


Fig. 5 Flexural strength test setup

4. Results and Discussion

4.1. Compressive strength

Compressive strength is one of its most important and useful properties of concrete. It usually gives an overall picture of the quality of concrete because it is directly related to the structure of the hardened cement paste. The average compressive strengths of concrete are presented in Fig. 6.

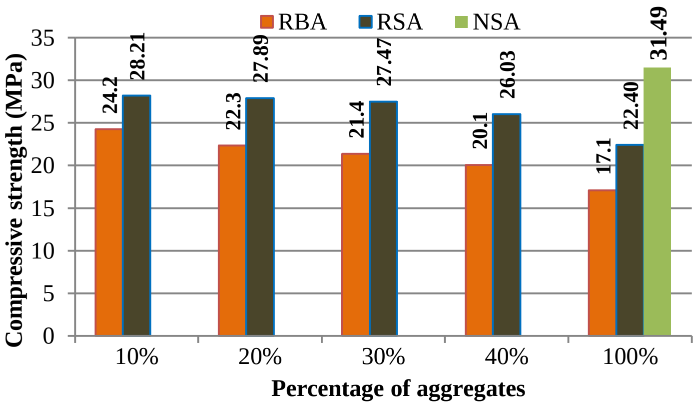


Fig. 6 Compressive strength for different % of aggregates

It was found that the compressive strength was from 28.21 MPa to 26.03 MPa for 10% to 40% RSA concrete. This strength of RSA concretre was from 17.3% to 29.76% greater than that of RBA concrete. It is mentioned in the Fig.6 that the strength of RBA concrete decreased linearly with a significant rate for increasing the percentages of replacement. On the other hand, the RSA concrete showed almost equal strength with small difference for up to 30% of RA. This result is in agreement with Rahal, [18], Xiao et al. [19], and Letelier et al. [20], maybe due to the added water for the workability correction. Since the amount of water also super-plasticizer were increased in the percentage of RCA, the amount of water was almost adequate with respect to absorption capacity of the aggregates. For this reason, small difference and linear change of compressive strength can be seen. In addition, a decrease in compressive strength can be responsible for the angularity difference of the NSA, RSA, and RBA. Compared to NSA, a dramatic fall in compressive strength was observed for concrete made with only RSA and RBA. The compressive strength of concrete containing 100% RSA was 5.30 MPa greater than the value of RBA concrete, and 9.09 MPa lower than the value of NSA concrete.

However, a major difference was observed in the failure pattern of concrete made with these two different types of RCA. Aggregate failure was seen in the concrete made with RBA and NSA (shown in Fig. 7) which can be occurred for the crashing of RBA at first due to its poor strength compared to NSA. Besides, combined failure was observed in RSA concrete, which is the possible explanation to the similarity strength characteristics of RSA and NSA. Only aggregate failure or only bond failure is not expected and acceptable to prepare good quality concrete. Therefore, it can be stated on the basis of this test result that RBA with NSA is not preferable in concrete mixes to produce good quality and desired strength concrete.

(a) NSA (b) NSA & RSA (c) NSA & RBA

Fig. 7 Failure appearance of concrete specimens under compressive load

4.2. Splitting strength

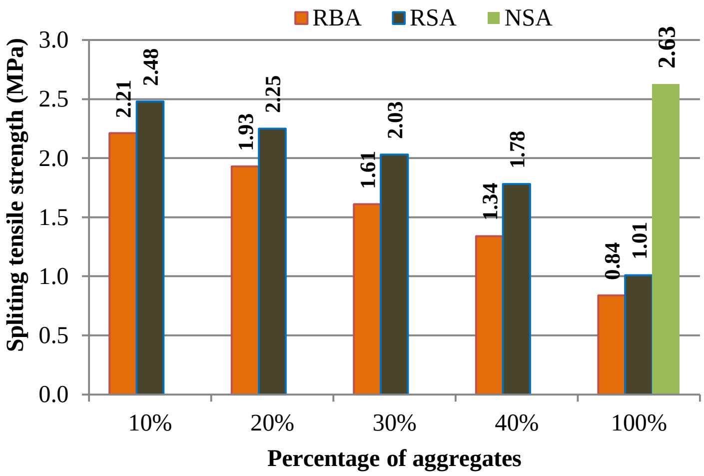
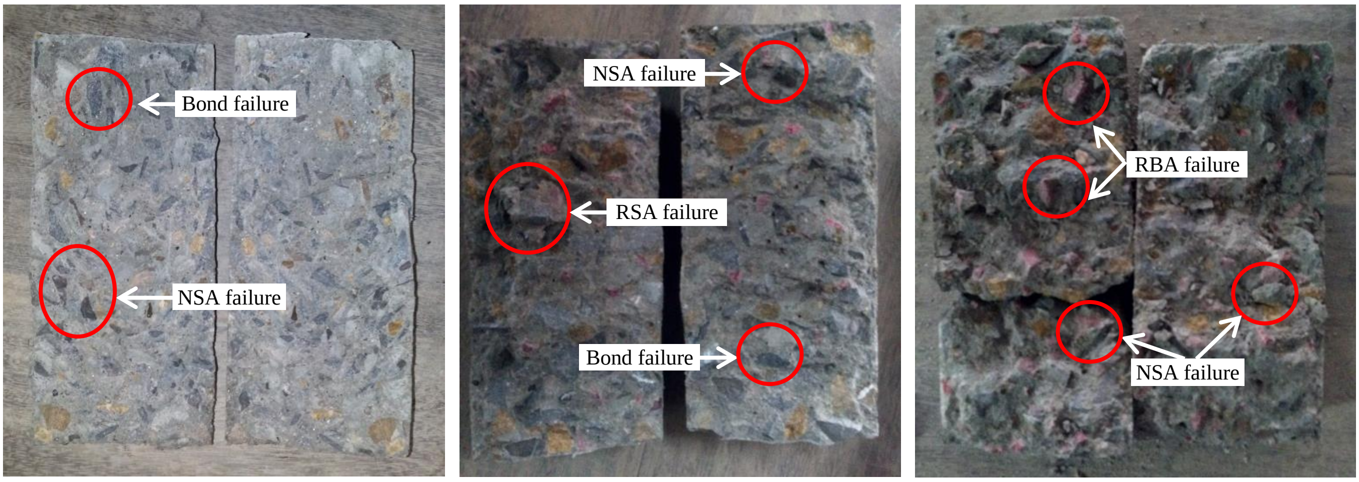


Fig. 8 Splitting strength for different % of aggregates



(a) NSA (b) NSA & RSA (c) NSA & RBA

Fig. 9 Failure appearance of concrete specimens under splitting load

Although concrete is not normally designed to resist direct tension, the knowledge of tensile strength is important in estimating the load under which cracking will develop. As it is difficult to determine the tensile strength of concrete by conducting a direct tension test, it is computed by flexural test and splitting test of concrete. The splitting strength test, however, was conducted at 28 days of curing and the average of the strengths for each percentage of RA presented in Fig. 8. It is clear in the figure that the splitting strength decreased gradually in both RSA and RBA concrete until 40% addition of RA. However, aggregate failure was seen for 30 to 100% RBA in concrete whereas combined failure was observed for all percentage of RSA. The appearance of failure surface for different coarse aggregates is shown in Fig. 9.

4.3. Flexural strength

Flexural strength depends on the dimensions of the beam and the arrangement of loading. In this experimental study, a single central point load was applied on a 150 mm×150 mm×450 mm prismatic specimen to determine the flexural strengths of concrete conforming to the ASTM standard requirements of the specification C293. The average flexural strengths of concrete specimens are presented in Fig. 10. As we can see, when the percentages of RA increased, the flexural strength of RSA and RBA concrete decreased. The concrete containing RBA was found from 5.05 MPa to 4.05 MPa for 10% to 40% replacement of NSA respectively which was approximately 15 to 31% lower than those of RSA concrete. In addition, the strength of 100% NSA concrete specimens was 2.52 MPa and 3.53 MPa greater than that of RSA and RBA concrete specimens respectively. In the test, the failure pattern of concrete specimens at the section of the applied center load was slightly different than compressive and splitting test. The bond failure was observed in the concrete containing 10 - 20% RBA and rest percentage of RA showed combined failure. On the contrary, combined failure was seen in all percentages of RSA except 100% in which mainly aggregate failure was found.

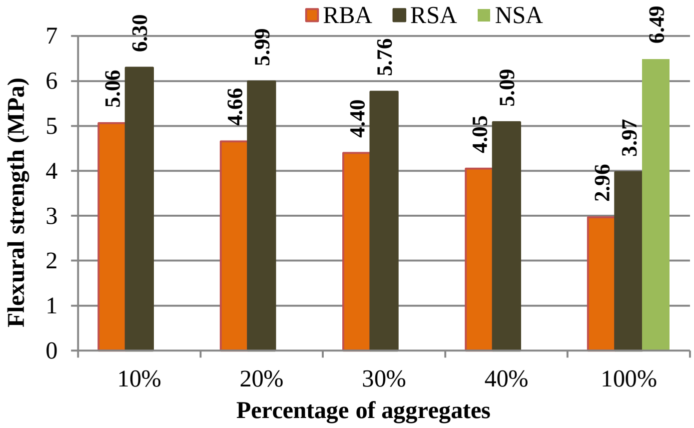


Fig. 10 Flexural strength for different % of aggregates

4.4. Dry unit weight

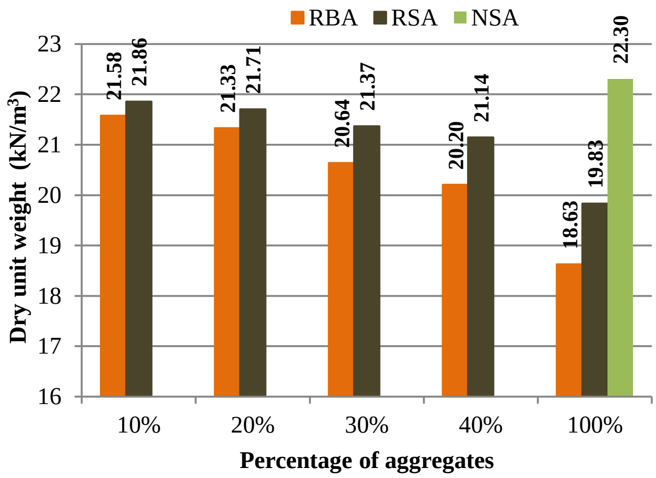


Fig. 11 Dry unit weight for different % of aggregates

Unit weight is the traditional terminology used to describe the property of concrete which is primarily affected by the unit weight of the aggregate, and varied by geographical location and increases with compressive strength depending on the added pozzolans. The dry unit weight of the cylindrical specimens was determined after 24 hours drying at room temperature at 28 days of curing and before compressive and splitting strength test. The average value of three specimens for each percentage of RA is presented in Fig. 11. Test results revealed that dry unit weight of concrete gradually decreased from 21.58 to 20.20 kN/m^3 and from 21.14 to 23.44 kN/m^3 of 10 to 40% replacement of NSA by RBA and RSA respectively. It is seen from the Fig. 11 that the different unit weight between RBA and RSA gradually increased when the percentage of RA increased. It is also observed that the unit weight of RBA and RSA concrete was about 3.5 kN/m^3 and 2.5 kN/m^3 lower than that of control specimen. This is due to a great different unit of NSA and RBA. The unit weight of RBA was 4.37 kN/m^3 lower than that of NSA, while RSA was 2.63 kN/m^3 lower than NSA.

4.5. Water absorption capacity

The absorption capacity of RA should be treated as one of the basic properties, which is to be taken into account while designing the mixture of new concrete on the basis of this aggregate. RA absorbs more water than the natural aggregate because of the attached mortar. The researchers of the University of Hong Kong recommended that the amount of RCA in structural concrete should be ranged from 20% to 30% in order to ensure that the maximum water absorption of aggregate is less than 5% [21]. The amount of absorbed water measured after 28 days of pond curing and the average values of the absorption capacity are presented in Fig. 12. Test results showed that RBA concrete has larger absorption capacity compared to RSA concrete and the amount of water absorption increased gradually for both types of RAs. It is noticed from the Fig. 12 that the absorption capacity is below 5% in the concrete specimens made from 10% to 30% RSA. On the contray, the absorption capacity value exceed 5% in the concrete made from 20% to 100% RBA. However, concrete made with only RBA had a higher percentage of water absorption, at about 15% which was approximately 3.0% greater than that of RSA whereas this value for NSA concrete specimens was only 3.13%.

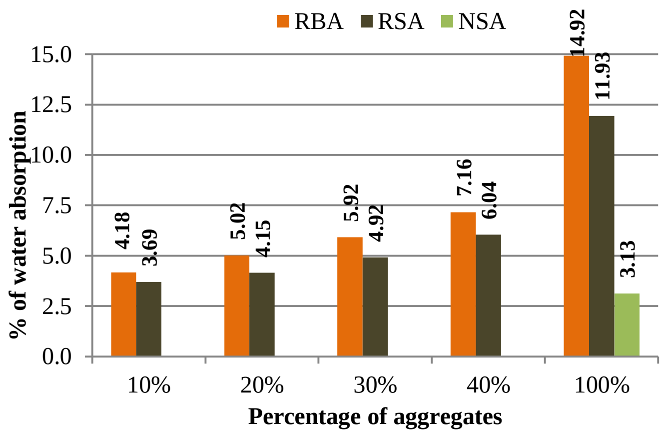


Fig. 12 Water absorption capacity for different % of aggregates

5. Conclusions and Recommendation

The experimental results obtained within the limited scope of this investigation led to the following conclusions:

(1) RSA concrete showed almost equal and good compressive strength for up to 30% replacement of NSA, whereas this strength decreased remarkably with the increasing percentages of RBA. In addition, a large variation of compressive strength was seen in the concrete made with 100% RBA, RSA, and NSA.

(2) Although the use of recycled aggregates reduces the flexural strengths, splitting strength and concrete density. The results of these strengths for RSA were higher than the results of RBA concrete. Whereas, RBA concrete absorbed a greater amount of water in comparison with its RSA concrete counterpart.

(3) Combined failure of concrete was seen for only 10% of RBA in concrete, but the rest of the percentages showed aggregate failure is undesirable for good quality concrete. On the other side, RSA showed combined failure for all percentages of aggregates.

To conclude, up to 30% RSA with NSA can be used for producing good quality concrete. On the other hand, RBA is not appropriate to be considered as a suitable alternative of NSA for normal concrete. However, in order to to know the detailed characteristics and to investigate the cracking behavior of concrete made with RBA and NSA, further studies is on modulus of elasticity test, shrinkage test, sorptivity test, and flexural test of beams with reinforcement are recommended.

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